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Experimental evaluation of thermal environment and ventilation effectiveness in a room heated by warm air

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SUMMARY
The study is focusing on experimental evaluation of the indoor climate in a residential room heated by warm air supplied by a mechanical ventilation system. The experiments were carried out in a full scale chamber, reproducing a typical residential room. The measurements were done for various positions of supply/exhaust, at different outside conditions, internal gains and air flow rates. Additional setups with floor heating were performed and compared with the warm air heating system. Vertical air temperature and air velocity profiles were measured in order to describe the thermal environment; contaminant removal effectiveness, air change effectiveness and local air change index were measured to express ventilation effectiveness in the room. Buoyancy forces play a key role in supply air distribution. No significant risk of thermal discomfort was noted. The ventilation effectiveness may strongly depend on the position of supply/exhaust; moreover, the three different ventilation effectiveness methods may yield different results.

IMPLICATIONS
In buildings with low energy consumption a mechanical ventilation system is often the only heating system used. The measurements investigate causes of thermal discomfort in rooms with such a heating system. It points out that the ventilation effectiveness in the occupied zone may be less than 1, apart from ventilation effectiveness assumed in standards.

KEYWORDS

Warm air heating, radiant heating, thermal environment, ventilation effectiveness

INTRODUCTION
In low energy houses the heating demand for space heating is getting very low and the use of the ventilation system also for heating could become an interesting alternative instead of installing a separate heating system. An acceptable indoor air quality in residential buildings is mainly defined by specifying the required level of ventilation in air changes per hour (EN15251, 2007), which may differ according to national standards. The listed levels of air change per hour in international or national standards are assuming full mixing i.e. ventilation effectiveness equal to 1. However, the resulting ventilation in air changes per hour is depending on the ventilation effectiveness. In existing standards the recommended values for ventilation effectiveness depend on position of supply and exhaust device and on the difference between supply and room air temperature (CR 1752, 1998). Especially by warm air heating supplying air at ceiling level the ventilation effectiveness may be than 1. The present paper reports on a study of warm air heating systems in an experimental room comparable to a residential room during winter season. The ventilation system includes several combinations of position of supply and return grills. Besides, a floor heating system was studied and

compared with warm air heating system. Evaluation of the possibilities and limitations are reported and discussed in the present work. Air temperature profiles, air velocity profiles, and ventilation effectiveness were measured under different boundary conditions and compared to the general criteria (ISO 7730, 2005) for a comfortable indoor environment.

METHODS

Room set up

The experimental measurements were carried out in a full scale chamber, equipped with a radiant floor heating/cooling and a ventilation system, set up to reproduce a typical residential room (Figure 1a). The heat loss through windows was simulated through radiant cooling panels located on one of the walls. Occupancy of the room was simulated using a thermal manikin, which allowed for calculation of equivalent temperatures. The measurements were done for various positions of supply/exhaust device, at different outside conditions, internal gains and air change rates. Additional setups with floor heating system were also measured and compared with the warm air heating system.

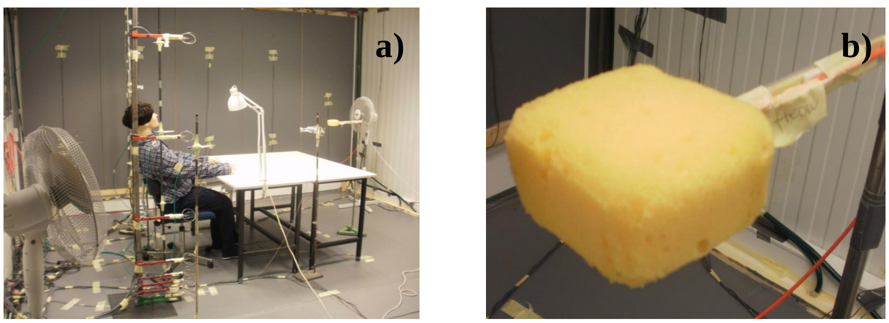


Figure 1. Pictures of: a) experimental residential room and b) simulated pollution source in the room.

Measurements

Vertical air temperature, air velocity profiles, operative temperature in a reference point and surface temperatures were measured in order to describe the thermal environment in the room. Contaminant removal effectiveness (CRE), air change effectiveness (ACE) and local air change index were used to express the ventilation effectiveness.

In CRE measurements a perforated table tennis ball covered by a sponge material served as a passive contaminant source in the room (see Figure 1b). The pollution was simulated using tracer gas R134a. The CRE measurements have been carried out in steady-state thermal and tracer gas concentration conditions. The air change effectiveness measurements were based on the mean age of air concept: *step-up method* was used, where constant tracer gas flow was admitted to the supply air duct and growth in tracer gas concentrations was continuously recorded. Mean age of air is calculated as the sum of the mean travelling time and the mean presence time (Breum, 1992). ACE is obtained as the ratio between the lowest possible mean age of air and the room mean age of air. An ideal piston flow is indicated by 100%, whereas 50% suggests full mixing. Local air change index presents the ratio between the mean age of air in the exhaust and the local mean age of air at the point of interest. At full mixing the age of air in the exhaust is the same as the age of air in the room and the ratio is equal to 100%. Details on procedure and indicators of ventilation effectiveness are explained in detail in (Mundt E et al. 2004; Breum, 1992; Fisk, 1997).

Room ventilation system

Three systems have been investigated. Positions of supply and/or exhaust and type of devices are shown in Figure 2. In System 1, air supply and exhaust were located at the ceiling. System 2 was designed with both, supply and exhaust device placed at the upper part of the back wall. Fresh air was supplied from the ceiling and removed by the exhaust device placed at the bottom level of the back wall in System 3.

In Figure 2a are shown the locations of thermal environment measurements indicated by the blue points (S) and of ventilation effectiveness measurements, marked by the green crosses (C). Whereas CRE has been performed at three heights (0.6m, 1.1m and 1.7m above the floor) in all points (C1, C2 and C3), local age of air has been taken at least in the point C1 at 1.1m above the floor. For case 3 of Systems 1 and 3 the local age of air has been taken in all positions (C1, C2 and C3) at 1.1m and 1.7m above the floor.

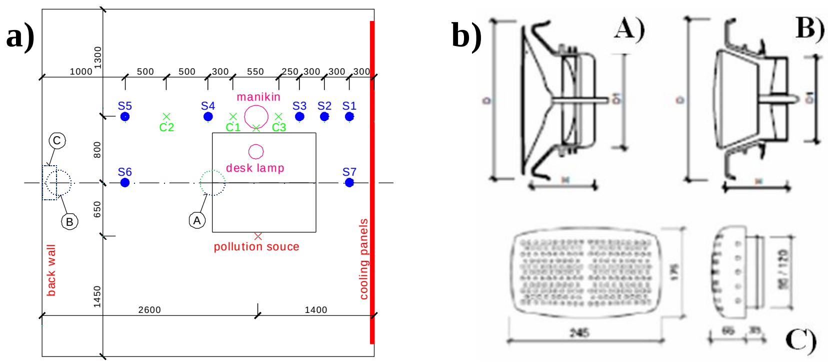


Figure 2. a) Experimental room set up with locations of measurement points and supply/exhaust devices; b) drawing of supply/exhaust used devices (A- supply at the ceiling, B – exhaust at the ceiling, C – supply/exhaust on the wall)

Analyses of room ventilation performance

The cases tested for particular systems are listed in Table 1. The air change rates were calculated as the ratio between the air flow rate in m^3/h and the volume of the chamber in m^3. The air change rates represent theoretical values only corresponding to the air flow rates in the Table at full mixing conditions. Cases P5 and P6 represent the room conditions under a combination of radiant floor heating and mechanical ventilation, the rest of the performed cases is with warm air heating.

Table 1. Simulated conditions for the experimental cases to be analysed

		P1	P2	P3	P4	P5	P6	P7
Air flow rate	(l/s)	5.6	11.2	5.6	11.2	5.6	11.2	16.8
Air change	(1/h)	0.5	1.0	0.5	1.0	0.5	1.0	1.5
Heat loss	(W)	-120	-120	-220	-220	-220	-220	-220
Heat gains	(W)	0	0	100	100	100	100	100
Overall heat balance	(W)	-120	-120	-120	-120	-120	-120	-120
System 1		☺	☺	☺	☺	☺	☺	☺
System 2		☺	--	☺	☺	☺	--	☺
System 3		☺	--	☺	☺	--	--	☺

RESULTS

Representative profiles of air temperature and air velocity for the occupied zone for the two heating systems are shown in Figure 3 (System 1, case 3). For the other two systems and for all the cases the profiles had the same tendency, eventually with small modifications. The results show no significant risk neither due to draught, nor vertical temperature asymmetry. Results of segmental equivalent temperature obtained from the manikin shown slightly increased risk of thermal discomfort due mainly to exposition of the left foot to the cold environment and downdraught nearby the cooling panels.

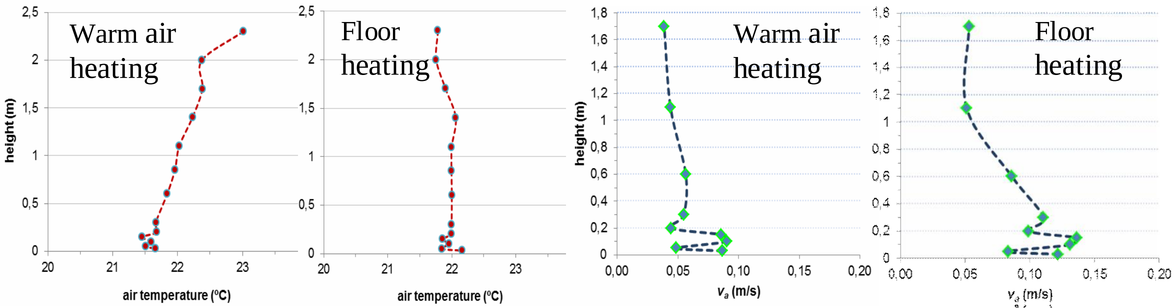


Figure 3. Air temperature and air velocity profiles for System 1, (5.6 l/s, 100W internal gains)

An average of CRE for all the performed room ventilation systems, measured at three locations in the occupied zone (C1, C2 and C3), is shown in Figure 4. The curves represent average values of the three warm air heating cases with internal gains (P3, P4 and P7). The trend reported in the graphs is representative of CRE as a function of the air flow rate (from 5.6 l/s to 16.8 l/s).

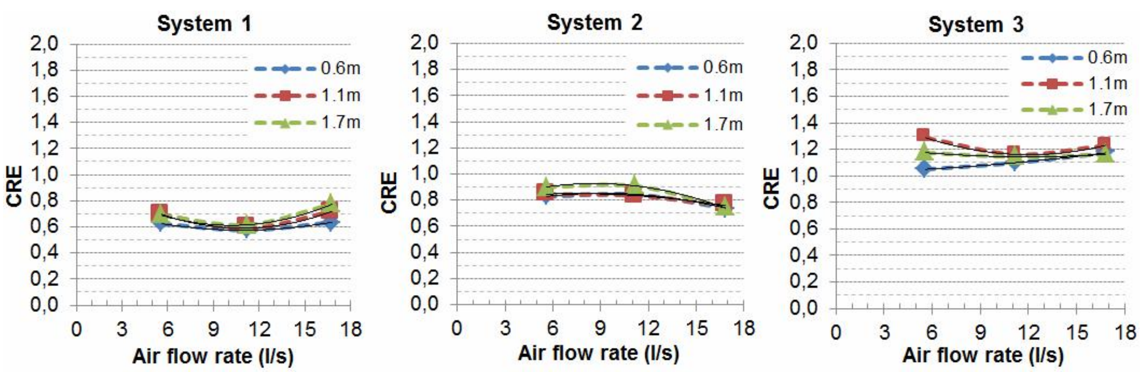


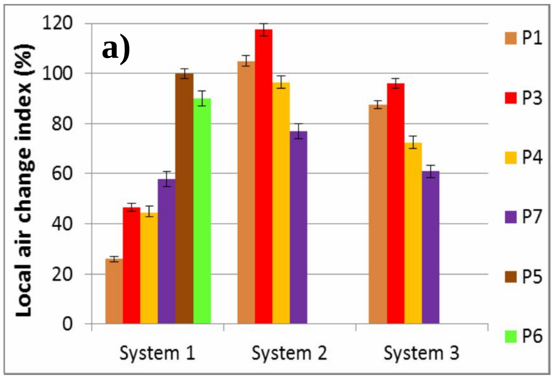
Figure 4. CRE as a function of air flow rate for warm air heating/ventilation (cases P3, P4 and P7). The curves represent average values measured in points C1, C2 and C3

In Table 2 the CRE (ε^c) for warm air heating system is reported compared with the CRE for floor heating system. For System 5 the CRE of warm air heating is substantially higher than for System 1 presented in the Table.

Table 2. Comparison of CRE (ε^c) for warm air heating and floor heating, System1

ε_v	Location	q = 5.6 l/s		q = 11.2 l/s	
		(warm air heating)	(mixing ventilation and floor heating)	(warm air heating)	(mixing ventilation and floor heating)
ε^c	C1	0.65	0.95	0.6	0.9
	C2	0.7	0.95	0.6	0.9
	C3	0.65	0.9	0.55	0.8
ε^c_{exp}	manikin	0.65	0.9	0.6	0.8

In Figure 5 are the results of air change effectiveness and local air change index for the three ventilation systems. The error bars in the left picture (local air change index) show uncertainty of the mean travelling time. The uncertainty represents the difficulty in determining exactly the time from molecules of tracer gas entered the space until it reached the measuring point. For case 2 ACE and local air change index were due to time reasons not thoroughly investigated and are therefore not presented in the Figure.



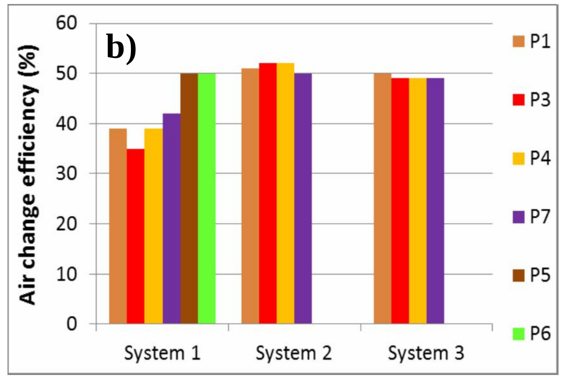


Figure 5. a) Local air change index for the three experimental ventilation systems at the point C1, 1.1m above the floor, and b) Air change efficiency of the three Systems

In case of ACE and local air change index, a set of measurements was performed with two fans present in the room, vigorously mixing the room air. The results at full mixing can be compared with the expected ideal values. They are briefly summarized in Table 3. One case was accomplished with floor heating, the rest with warm air heating. Moreover, System 1 was uninstalled and installed again later, and three experimental cases were repeated. The maximum difference of 1 % for ACE and 8 % for local air change index was found.

Table 3. Arithmetic mean of ACE with standard deviation for cases with full mixing

	Air change efficiency			**Local air change index**		
	System1	System2	System3	System1	System2	System3
Mean	49,8	48,7	50,1	97,6	94,7	98,1
St. deviation	0,3	0,6	0,1	2,2	3,5	0,4
No. of measurements	5	3	3	5	3	3

DISCUSSION

Whereas temperature gradient occurs in warm air heating, in case of floor heating the air temperature is evenly distributed. Slightly increased velocities have been found in lower parts for warm air heating, caused by downdraught of warm air supplied in upper parts, descending to the occupied zone nearby the cooling panels and moving above the floor. In case of floor heating the movement may be a result of downdraught and interaction of the room air with the warm floor. If we compare CRE of warm air heating and floor heating systems, mainly for System 1 the CRE was better for floor heating, indicating conditions close to full mixing, whereas results for warm air heating indicate short-circuited flow, as could have been expected (Figure 4). This can be also seen looking at Figure 5. Best CRE was noticed for System 3 with the exhaust at the floor level, where the CRE was even higher than 1. System 2 represented an alternative between the other two systems. However, in System 2 noticeable is the decrease of CRE at higher air flow rates. Altogether, the results point out the importance of the location of the air supply and also of where it is exhausted. Looking at Figure 5b, the results of ACE for System 1 indicate a short-circuited flow pattern, and thus decreased ventilation effectiveness. In other systems the results suggest conditions close to complete mixing. However, looking at local air change index in Figure 5a, we can find differences between particular cases. Systems 2 and 3 show impairing air distribution to the measuring point with increasing air flow rate. Lowest values have been noticed for System 1, indicating markedly short-circuited air flow between supply and exhaust, both placed on the ceiling. The explanation of higher local air change index at lower air flow rates for Systems 2 and 3 might be a relatively higher contribution of buoyancy forces to the total air movement in the room compared to the forced ventilation. With increasing air flow rate more fresh air is introduced to the room, but the increase is not proportional to the increase in the amount of fresh air supplied to the measurement point. Consequently, relatively more fresh air is exhausted at higher air flow rates. Influence of buoyancy forces on the air flow pattern is supported by the fact that for all Systems with warm air heating the results of ventilation effectiveness were worse without internal gains. This might have been caused both by lower temperature of cooling panels and missing effect of thermal plumes generated by the heat gains.

CONCLUSIONS

In none of the Systems investigated significant risk of thermal discomfort due to vertical temperature asymmetry or draught occurs, however, local cooling of certain body parts might occur nearby windows as a result of cold surfaces and downdraught. Whereas the effect of warm floor and cold air supplied to the room is conditions close to full mixing, for warm air heating systems it may be very important where the supply and the exhaust devices are located. Although the real conditions would differ to certain extent, the results suggest that cold surfaces and internal gains have an important influence on the room air distribution. Even in applications where the exhaust is not located in the same room, the fact whether the doors are open or whether the air is exhausted through a leakage under the door could influence the distribution of the air and ventilation effectiveness significantly.

ACKNOWLEDGEMENT

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